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SYNOPSIS

Size scale in cavitation erosion is a major problem confronting the design engineers of modern high-speed machinery. An overview and erosion data analysis presented in this paper indicate that the size scaling exponent n in the relation Erosion rate $\propto$ (Size or Diameter)^n can vary from 1.7 to 4.9 depending on the type of device used. There is, however, a general agreement of exponential values n if the correlations are made keeping the cavitation number constant.

NOTATION

D	diameter or size of cavitation inducer
D_t	diameter of impeller
d	diameter of cavitation bubble
H	head of turbine
m	exponent in Eq. (3)
N_s	specific speed
n	exponent in Eqs. (1) and (2)
P	pressure inside cavity
p	pressure of flowing system
R	correlation coefficient
V	velocity of flow
σ	cavitation number, $(p - p_v)/(1/2\ \rho V^2)$
ρ	mass density of liquid

Subscripts:

v	vapor
1	first cavitation inducer
2	second cavitation inducer

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INTRODUCTION

Size scale effects[1] in cavitation erosion have been plaguing design engineers for many years. This problem is due to the complex interactions of the eroded area and the collapse energy of the cavitation bubbles as the size of a component changes. There has been a general understanding that true damage size scale effects are those encountered at a constant cavitation number σ [$= (p - p_v)/1/2\ \rho V^2$], with variation in velocity or pressure, while the size parameter is varied [1,2].

Generally with flow venturi [3-5] and rotating disk [3,6] devices, maximum erosion occurs at a particular characteristic (cavitation inducer) size[2] when the flow characteristics are independent of Reynolds number. Hence, most of the earlier scaling effects were concentrated in the region where erosion rate increased with the size of the cavitation inducer (circular cylinders, prismatic sources, or holes). The size scaling exponents reported by various investigators are presented in Table 1. The size scale effects are generally expressed as

$$\text{Erosion rate} \propto (\text{Size})^n \qquad (1)$$

or

$$(\text{Erosion rate})_1/(\text{Erosion rate})_2 \propto [(\text{Size})_1/(\text{Size})_2]^n \qquad (2)$$

[1]Considering cavitation damage tests wherein suppression pressure is varied but velocity is held constant, cavitation number varies as determined by the variation of suppression pressure. It is obvious that these tests will result in large changes in cavitation damage rates and these results are called "pseudo scale effects". "True damage scale effects" are defined as those tests for which the cavitation number and flow geometry are constant.

[2]Throughout this paper the term size and diameter are used interchangeably when referring to the cavitation inducer.

Details pertaining to the type of device, the test conditions, the materials tested, and the stage of erosion are also presented in Table 1.

The present investigation was conducted to review and examine the agreement of exponential values n with erosion obtained in different laboratory and field devices when the cavitation number is kept constant. The variation in the value of n is discussed for general applications.

Theoretical Formulations

Theoretical formulation of size scale effects and their experimental verification in a flow cavitation system have been considered only by a few investigators. Thus, Shalnev, et al. [7,8] derived a detailed energy parameter in terms of the erosion volume and the work done by the cavitation drag forces by considering the following parameters: (1) the state and structure of the cavitation zone, (2) the relative dimensions of the model, (3) the cavitation layer thickness, (4) the characteristic model dimension, (5) the flow velocity, (6) the specimen erosion volume, (7) the experimental duration, and (8) the Reynolds and Weber numbers that are likely to affect the intensity of erosion.

Malyshev and Pylaev [9] formulated a relationship between the volume loss of material and the size of the geometrically similar venturi nozzles by using the assumptions: (1) the Strouhal number remains constant for all nozzles when the geometrical, kinematic, and cavitation similitudes are met with; and (2) the number of cavitation impulses per unit of time is proportional to the cavity-shedding frequency.

Kato [10] provides new set of scaling laws by using the energy distribution of the cavitation bubbles. The mean depth of deformation rate was expressed in terms of flow velocity, characteristic length, hardness, and ultimate resilience. The size scaling exponent covered a very large range for the examples chosen.

Thiruvengadam [11,12] developed several scaling laws by using (1) the concepts of erosion strength [13], (2) the intensity of cavitation bubble collapse [11], and (3) energy efficiency calculations [12]. According to this formulation, cavitation intensity theoretically varies linearly with the characteristic length. Stinebring, et al. [14] recently suggested an energy parameter that considers scaling effects during the incubation period.

Experimental Studies

Rata [15] reports a size scale exponent of $8 < n < 8.3$ from experiments with thin zinc and brass plates. Shalnev, et al. [7,8,16], using a flow venturi, obtained for lead an exponent of $n = 3$ during the incubation period and an exponent of $n = 4$ during advanced stages of erosion. Malyshev and Pylaev [9] obtained $n = 3$ for geometrically similar nozzles with lead overlays.

Meier and Grein [17] for pumps and pump-turbines as well as Schiele and Mollenkopf [18] for hydroturbines suggest a value of $n \simeq 3$. Experience in the hydroturbine industry [2] also confirms this value. However, Lashkov [19] used a value of $n = 2$ for hydraulic turbines in developing a method to predict the erosion on blades and rotors of different materials.

The studies of Hutton and Lobo Guerrero [20] with aluminum foils tested in two venturi devices indicated exponents of $2.2 < n < 3.5$. For a water jet propulsor, Conn and Mehta [21] assumed an exponent of $n = 1$ due to lack of information on size scale effects. Analysis of experimental data [12] by Mehta and Conn [22] resulted in an exponent of $n = 2.5$ for rotating foils, although the theoretical scaling laws [12] predict a linear relationship between the intensity of erosion and the characteristic length of the foil.

Hackworth [23], while predicting cavitation erosion of ship propellers from the results of model experiments, found that the average pit diameter varies as $(\text{Size})^{2.3}$. Reviews by Hammitt, et al. [1,24] suggest that the exponents would go as high as 5, and this is predicted by Canavelis [25].

Systematic experimentation and analysis are necessary to understand size scale effects and to realize the limitations of the current knowledge.

EXPERIMENTAL DATA AND ANALYSIS

Erosion Data

The data obtained by different investigators using venturi [3-5] and rotating disk [6,26,27] devices over a number of years were analyzed to determine whether the exponents reported in the literature for size scale effects are valid for these two devices and other similar field devices.

Analysis

Experimental data obtained in rotating disk [3,6,26] and venturi [3-5] devices are presented in Figs. 1 to 3 as average erosion rate[3] versus the diameter of the cavitation inducers. Although systematic studies using rotating disk devices with varying sizes of holes were conducted by Lichtman, et al. [28] and Wood et al. [29], sufficient details are not available for comparison. As discussed in the introduction, the results in Figs. 1 to 3 indicate that for both these devices there is a critical maximum cavitation erosion at a particular inducer size. It is clear from Fig. 1 that exponents varied from 1.8 to 4.0 for aluminum with smooth and rough cavitation inducers. On the other hand, the exponent for copper tested in a venturi was 1.7. The plots in Fig. 2 indicate the values $4.3 < n < 4.6$ with equilateral prisms as cavitation inducers and $3.3 < n < 4.9$ with circular cylinders as cavitation inducers for aluminum tested at constant cavitation number in a rotating disk device. Figure 3 indicates $4.1 < n < 4.2$ for the venturi device agree approximately with the exponents for the rotating disk device shown in Fig. 2, in spite of the differences in the two experimental devices. Furthermore, in Fig. 3 the erosion rates were chosen in such a way that the cavitation number was almost constant. The exponent $n = 3$, reported for a venturi device [7,8] and for nozzles [9] and adopted for pumps [17,18] and hydroturbines [9] by other investigators was not obtained for all stationary and rotating component data sets. Hence, exponents from 1.7 to 4.9 can be applied to rotating and venturi devices.

DISCUSSION

It is generally believed that the area of erosion varies as the square of the characteristic size of the cavitation inducer [2]. Experimental data presented in Fig. 4 indicate $m = 1.59$ for rotating disks [3,26] and $2.7 < m < 3.4$ for venturi devices [4,5] with circular cylinders, using a relationship

[3]Most of the experimental data used herein have been obtained for different type of studies. Hence, the erosion rates were calculated as an average over the entire test duration and were called average erosion rates. The instantaneous erosion rates were used by other investigators.

$$(\text{Area of cavity or Erosion}) = (\text{Diameter})^m \quad (3)$$

However, the average bubble size attained will be larger for larger inducers as the bubble will be exposed longer to the same reduced pressures [2]. This results in high bubble collapse energy, and this energy is proportional to Pd^3. The exponents obtained in the present analysis (Fig. 4) provide an insight into the differences between the simple area effect and the actual experimental data with both rotating disk and venturi devices. The data in Fig. 4 correspond to a constant cavitation number. Hence, it appears that the area of erosion or cavity varies more than the simple area rule for stationary components and this effect may possibly be reflected in the size scale effects as well.

For the data of Figs. 1 to 3 the high exponential values can be attributed (1) to too small a variation in size (in some cases), (2) to the experimental points corresponding to different stages on the erosion-rate-versus-time curves, (3) to varying intensity of erosion, (4) to varying cavitation number (in a few cases), and (5) to not using geometrically similar cavitation inducers. (In most studies the inducer diameter, or size, was increased but not the height. However, this was not done with test sections of venturi devices or disks of rotating disk devices.) Plots in Figs. 2 and 3 show, however, that the results with constant cavitation number can yield exponents as high as $n = 4.9$ Furthermore, the plots in Fig. 2 were obtained from the corresponding stages of erosion-rate-versus-time curves at constant cavitation number. Hence, the stage of erosion and the minor variation of cavitation number are of negligible significance at least in the present analysis (Figs. 1 to 3). However, too small a variation in size, large variations in cavitation number, and intensity of erosion certainly seem to contribute to the deviations in the exponents. In this analysis, the values $1.7 < n < 4.9$ are thought to be reliable and repeatable. This is in close agreement with the exponents of 2 (simple area rule) to 5 reported earlier [2]. However, the values $8 < n < 8.3$ reported in the literature [15] have also to be considered as an extremity using thin plates.

Furthermore, in view of the variations in size scale exponents, a detailed study involving a proportionate variation of the height of the inducer to its diameter or size (keeping the optimized aspect ratio) for different materials at a constant cavitation number is necessary to further understand size scale effects in rotary and stationary devices. Another additional factor that also requires consideration is that of changing the test sections geometrically (similar to Shalnev, et al. [7,8,16] studies).

The following factors need to be considered in order to obtain a universal understanding of the size scale effect: (1) limiting source size to a particular characteristic length in order to reduce excessive velocity gradients on the surface of the specimens tested in a rotating disk device, (2) avoiding choking flows in venturi devices and supercavitation in rotating disk devices, (3) correlating data from the corresponding stages of erosion-rate-versus-time curves, (4) using Eq. (1) with many points (Eq. (2) may lead to maximum deviation of n as only two points are involved), and (5) considering the effects of surface roughness, Reynolds number (including viscous and inertia-dominated flows), Weber number, and vortex-shedding frequency. Unless all of these factors are accounted for, size scale effects will continue to plague design engineers. (Exponents obtained by using damage data taken during the incubation period and involving pit counting may indicate different scale effects.)

CONCLUSION

The data obtained by the present authors and other investigators in venturi and rotating disk devices over a number of years have been analyzed in order to understand the deviation of the size scale exponent for different types of experimental devices and conditions.

The exponents $1.7 < n < 4.9$ are reliable for venturi as well as rotating disk devices at a constant cavitation number. This range of exponents is very close to the values of 2 (simple area rule of cavity, i.e., Area of cavity = $(\text{Diameter})^2$) to 5 reported in the literature.

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TABLE 1. - EXPONENT n FOR SIZE SCALE EFFECTS

[Erosion rate] = $[\text{Diameter}]^n$ or $[(\text{Erosion rate})_1/(\text{Erosion rate})_2] = [(\text{Diameter})_1/(\text{Diameter})_2]^n$

Investigator	Equipment	Test conditions	Material	Exponent, n	Remarks
Shalnev, et al. [7]	Venturi	Velocity, 12 m/sec; circular cylinder; aspect ratio, 1	Lead	$^a3$	Using critical point of erosion[c]
Shalnev, et al. [8]	Venturi	Velocity, 12 m/sec; circular cylinders; cavitation inducer diameters, 24 and 48 mm; aspect ratio, 1	Lead	$^a3$ $^a4$	During incubation period During erosion
Shalnev, et al. [16]	Venturi	Velocity, 12 m/sec; circular cylinders; cavitation inducer diameters, 24 and 48 mm	Lead	$^b3$ $^b4$	During incubation period During accumulation period
Canavelis [25], referenced in [2]	------	Theoretical	---------	5	-----------------------
Meier and Grein [17]	Pump and pump-turbines	Complete operating range	Stainless steel	$^d3$	[Cavitation intensity] = $[\text{Delivery head}]^n$
Schiele and Mollenkopf [18]	Pump	---------------------	---------	$^d3$	
Malyshev and Pylaev [9]	Venturi type of geometrically similar nozzles	Velocity, 36.5 m/sec; pressures, 0.198 and 0.628 MPa; cavitation inducer diameters, 1, 2, 4, 6, and 8 mm; cavitation number, 0.44	Lead[e]	$^f3$	Cavitation pitting
	Hydroturbines	Impeller diameter, 5.5 mm; head of turbine, 10 m; specific speed, 125 rpm Impeller diameter, 1.2 mm; head of turbine, 90 m; specific speed, 500 rpm	Stainless steel[g]	----------	Cavitation pitting
Hammitt [2]	Hydroturbines	Not available	---------	~4	-----------------------
Hutton and Lobo Guerrero [20]	Venturi devices	Velocity, 5 to 45 m/sec	Aluminum foil	2.2 to 3.5	-----------------------
Ramamurthy and Bhaskaran [6]	Rotating disk	Velocity, 39 to 46 m/sec; cavitation number, 0.196; circular cylinders and wedges as cavitation inducers	Aluminum 1100	3.3 to 4.9[h]	During erosion
Rata [15]	Schröter-Walcher type	Velocity, 30 to 40 m/sec	Thin zinc and brass plates	8 to 8.3	-----------------------
Mehta and Conn [22], data adopted from [12]	Rotating foil device	Velocity, 48.8 to 59.1 m/sec; 3.8- to 7.5-cm foils	---------	2.5	-----------------------

[a]Theoretical formulation has provided an exponent of 3 [7,8].
[b]Accurate formulation of theory has provided an exponent of 4 [16]. As the erosion develops, the exponent increases.
[c]Critical point has been calculated from the plot of acceleration of damage versus cumulative damage or exposure time.
[d]Adopted value from the literature. This value has not been established by the authors.
[e]Test specimens with lead overlay were used for studying separate cavitation pulses. Shape and size of pits on polished lead surfaces were measured. Volume loss of the specimens was, however, evaluated with a graphite-lead hard-pressed plastic overlay.
[f]Theoretical analysis also provided n = 3 in the relationship (Volume loss of material) = $(\text{Size})^n$.
[g]Both base material and welds have been used. To increase the pitting rate, the zone of cavitation pitting was attached to the surface with annealed aluminum.
[h]Computed by the present authors from data.

PARAMETER	DEVICE		
	ROTATING DISK		VENTURI
	DATA SOURCE		
	[3]	[26]	[3]
TEST FLUID	TAP WATER	TAP WATER	TAP WATER
VELOCITY, m/sec	36.6	32.6	30.18
ABSOLUTE PRESSURE, MPa	0.143	0.140	0.481
HEIGHT OF INDUCER, mm	3	3	12.7
TEST TIME, hr	6	6	10(Al); 20(Cu)
MATERIAL	ALUMINUM	ALUMINUM	ALUMINUM AND COPPER
INDUCER SURFACE	□ SMOOTH ■ ROUGH	△ SMOOTH	● Cu(SMOOTH)

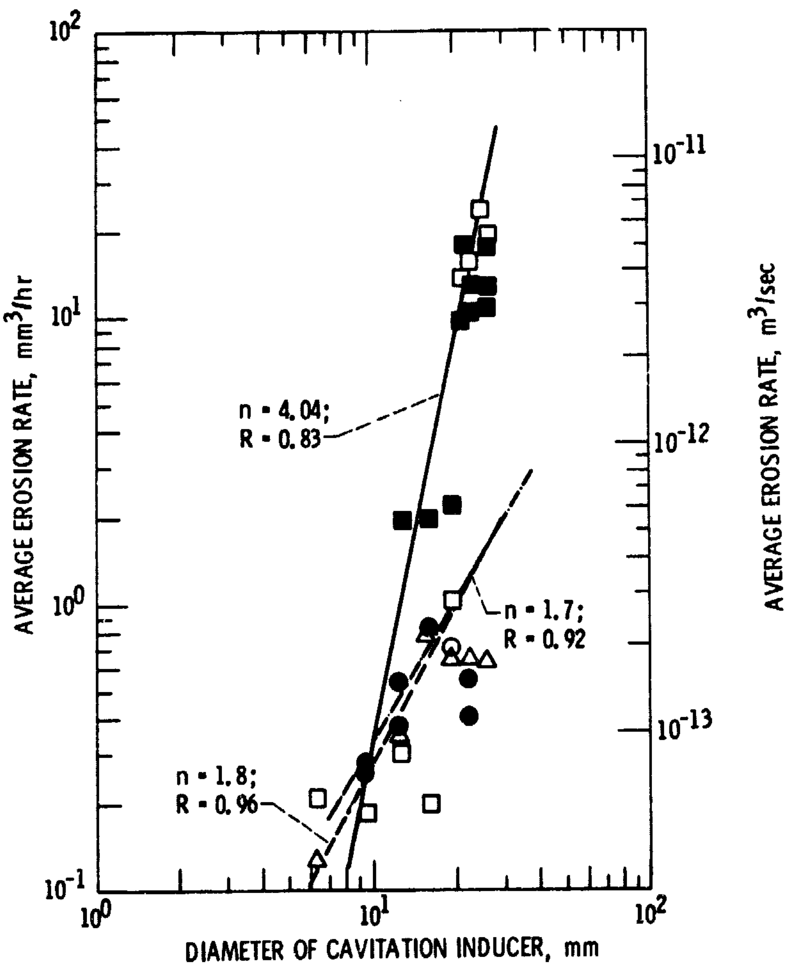

Figure 1. - Average erosion rates of aluminum and copper as a function of diameter of inducer for rotating disk and venturi devices. (Data sources, [3], [26].)

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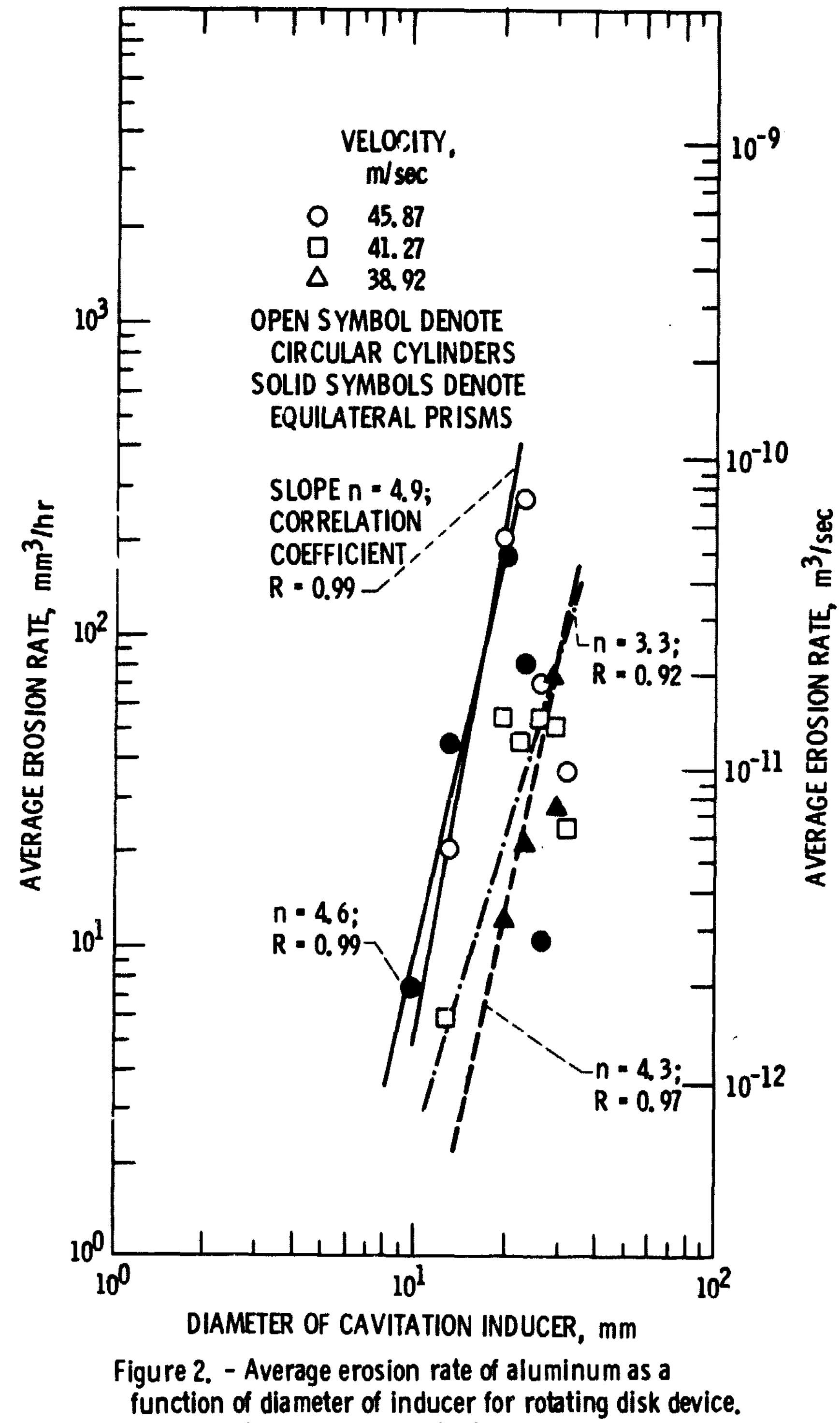

Figure 2. - Average erosion rate of aluminum as a function of diameter of inducer for rotating disk device. Exposure time, 30 min; cavitation number, σ, 0.196. (Data source, [6].)

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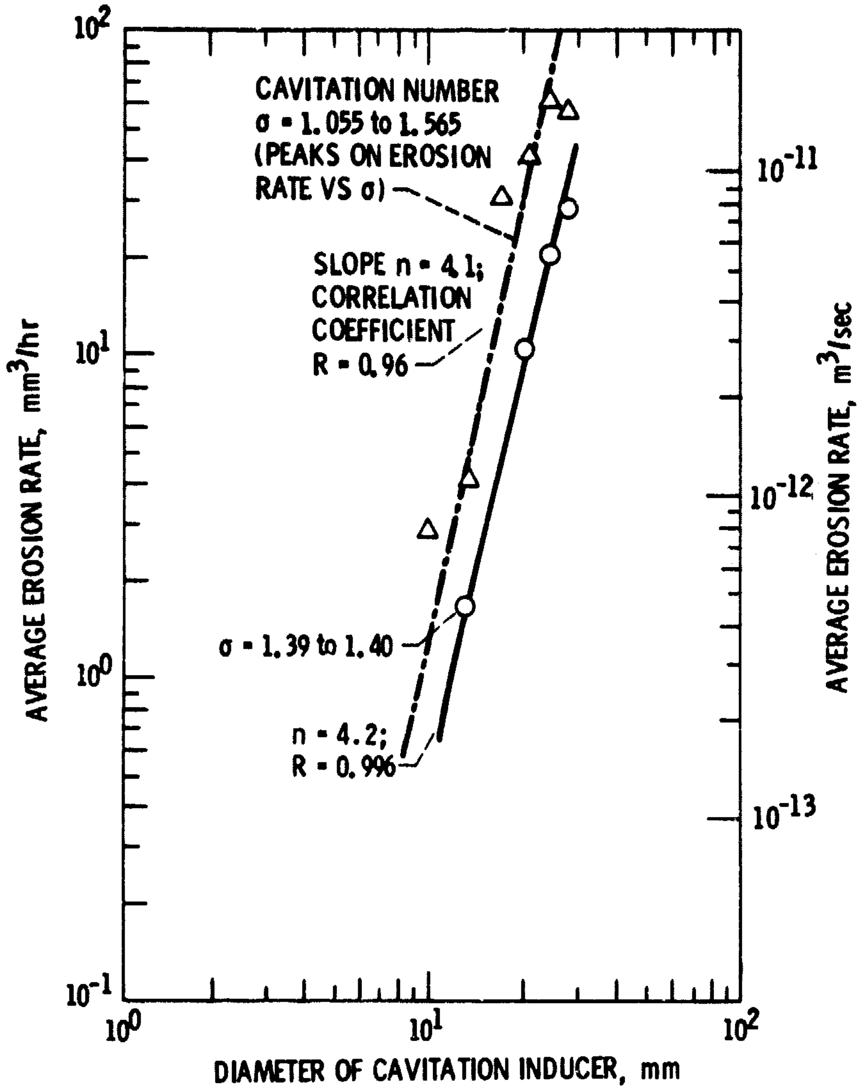

Figure 3. - Average erosion rate of aluminum as a function of diameter of inducer for venturi device. Exposure time, 6 hr; height of inducer, 12.7 mm; velocity, 27.45 m/sec (Data source, [4].)

	EXPONENT IN EQ. (3), m	CORRELATION COEFFICIENT, R	CAVITATION NUMBER, σ	DEVICE	AREA OF-
○	2.73	0.97	1.5 to 1.53	VENTURI (27.45 m/sec)	CAVITY
●	3.36	.99	1.51	VENTURI (27.45 m/sec)	EROSION
□	1.59	.99	-----------	ROTATING DISK	CAVITY

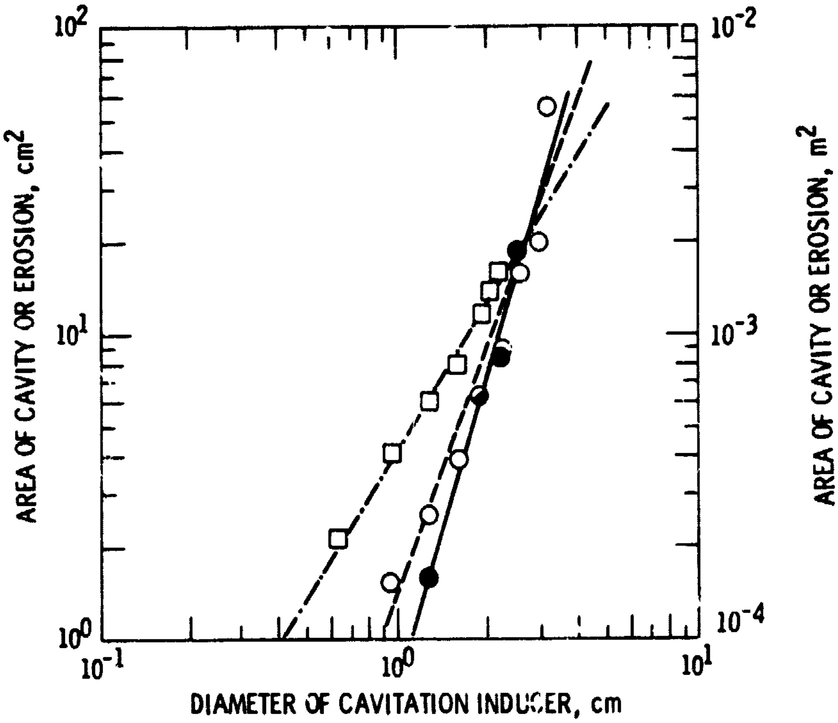

Figure 4. - Area of cavity or erosion as a function of diameter of cavitation inducer for aluminum specimens. Area of cavitation or erosion ∝ (Diameter)^m. (Data sources, [3, 4].)